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The relationship between carbon fixation and dendrometric characteristics of native species in São Paulo's forest fragments

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Abstract: The increase in carbon dioxide (CO₂) implies the intensification of the greenhouse effect, since from a quantitative point of view it is the most responsible for the process. The result of this effect is the disturbance of the energy balance between the earth and the atmosphere, causing climate change on the planet. There is the possibility of reducing greenhouse gas emissions to the atmosphere through planting with forest species, combined with sustainable reforestation and afforestation techniques in areas that have suffered human disturbance. In this context, our goal is to evaluate the potential for carbon sequestration and fixation in three forest fragments in the Tottori friendship forest in the City of São Paulo at eight years of age for 35 forest species. The species were grouped into four distinct groups, with distinct main characteristics. However, it was observed that 28 from 35 species do not present an outstanding characteristic for the grouping. The other seven species stood out for presenting dendrometric characteristics with carbon sequestration and fixation, specifically *Clitoria fairchildiana* and *Samanea tubulosa*. Among the characteristics that are most related to carbon sequestration and fixation were DBH, Stem volume and total volume, wood density was the characteristic that was least correlated with the others evaluated. It is recommended that an assessment be carried out at older ages to verify whether the grouping and values of carbon sequestration and fixation change over time, and possibly explain how the botanical family of a given species can influence carbon sequestration and fixation and plantations of forest fragments.

Keywords: carbon sequestration, climate change, global warming, forest species potential, reforestation.

Introduction

Climate change is the phenomenon associated with the degradation of natural resources, including deforestation, inadequate land use, burning of fossil fuels and other anthropogenic activities that lead to the emission of gases into the atmosphere such as carbon dioxide, methane and nitrous oxide, called Greenhouse Gases (GHG), and its main components are CO₂, CH₄, N₂O and chlorofluorocarbons (CFCs), which are highly capable of absorbing long-wave radiation. Which are emitted by the atmosphere and the terrestrial surface, causing terrestrial heating (U.S. Energy Information Administration, 2021). The increase in carbon dioxide (CO₂) implies the intensification of the greenhouse effect, since from a quantitative point of view it is the most responsible for the process. The result of this effect is the disturbance of the energy balance between the earth and the atmosphere, causing climate change on the planet. Terrestrial ecosystems specifically forest ecosystems comprising vegetation and soil are considered carbon sinks. Appropriate management of the terrestrial biosphere, particularly land and forest use, can significantly reduce the increase in greenhouse gases.

According to Renner (2014), the concept of carbon sequestration refers to procedures for assimilating and storing atmospheric carbon dioxide, in order to minimize impacts on the environment. The process involves the containment and reversal of the accumulation of atmospheric carbon dioxide, aiming to reduce the greenhouse effect.

Carbon sequestration by forestry activities is based on assumptions. First, carbon dioxide is an atmospheric gas that circulates around the world, and consequently, efforts to remove GHGs by forests will have the same effect, whether they are applied close to the emitting source of pollutant or on the other side of the world. Second, green vegetation removes carbon dioxide from atmosphere through photosynthesis, converting it into organic compounds used in plant growth and metabolism. In this way, woody plants store carbon in wood and other tissues until death and decomposition, a phase in which the carbon in wood can be released in the form of carbon dioxide, carbon monoxide, or methane, or it can be incorporated into the organic substance in the soil, the latter being the only one beneficial for the conservation of ecosystems (Silva, 2015).

According to Arana and Boin (2013), carbon sequestration through reforestation can provide an income opportunity for its investors to gain recognition for their environmental service. Economic rationality takes the issue of global climate change very objectively. Capital opens up to incorporate the environmental issue in different ways: on the production side, new markets, competition and the environmental image.

A forest fragment can be defined as any area of continuous natural vegetation, interrupted by

anthropogenic or natural barriers, capable of significantly reducing the flow of animals, pollen and/or seeds (Rogan and Lacher-Júnior, 2018). Fragmentation results in the loss of biodiversity, causing instability in populations, communities and ecosystems.

The conservation and restoration of forest fragments is justifiable and necessary, as these are of great environmental and social importance. Because these areas perform environmental functions, e.g., protecting the soil and maintaining watercourses; they can sequester atmospheric carbon, mitigating the negative effects of climate change; and, in the context of landscape ecology, they can allow a greater connection between forest fragments and reserves, functioning like ecological corridors for animals and forest species (Higuchi et al. 2012).

In 2012, the then Instituto Florestal (currently together with the then Institutos de Botânica and Geológico merged in Instituto de Pesquisas Ambientais), and Tottori-Kenjin Cultural Association, in partnership with Florestas Inteligentes, promoted the planting of more than 330 trees from 70 species from the Atlantic Forest, in celebration of the 60th anniversary of the Association.

Planting trees were donated by the company Florestas Inteligentes through the Florestas da Gente Program. The initiative aims to symbolize the friendship between São Paulo and Tottori with a lasting milestone, uniting immigrants from that province, their descendants, the provincial government and the population in general in the recovery of Atlantic Forest. Tottori is the province with smallest population, 600 thousand inhabitants, among the 47 provinces of Japan. It sent around 2000 immigrants to Brazil during the period of Japanese immigration. The Association was born from a campaign by Japanese immigrants from the province of Tottori (Bucci, personal communication).

Considering the importance of studies on CO₂ sequestration and fixed of native tree species, we selected 35, 8-year-old species, for our study. Our goal was to determine carbon fixed, and compare dendrometric characteristics, separate them through cluster analysis and detect the most important variables for such separation at São Paulo-Tottori Friendship Forest.

Materials and Methods

Sampling

São Paulo-Tottori Friendship Forest is in Alberto Löfgren State Park (PEAL, Portuguese) is in the northern area of São Paulo City, São Paulo State, Brazil (23°47'S, 46°38'W, elevation 814 m). Climate is Cwa in the Köppen classification, mesothermal and humid with rainy summers and dry winters (Rossi et al., 2009). Ombrophilous Dense Forest is the main vegetation formation of PEAL; anthropic areas are also found with arborets of one or more species (Arzolla et al., 2009). The trees

investigated in this study are in in three fragments (Figure 1). In 2012, 330 trees of 70 species from the Atlantic Forest were planted at the site with 3 x 2.5 m spacing, (Secretária de Infraestrutura e Meio Ambiente do Estado de São Paulo, 2021). In the present study we investigated 35 species due to availability of sufficient data for statistical analyses.

Wood density

Wood density was calculated according to NBR 11941, Brazilian Association of Technical Standards - ABNT (2003). The samples were saturated in water until the wood presented moisture above the fiber saturation point, then they were dried in ovens until they presented constant mass, we use ten bodies of evidence for each clone. The basic density was obtained according to equation 1:

$$\text{Wood density} = \frac{Dm}{Sv} \quad \text{Eq. 1}$$

Where: Dm: Dry mass (g) and Sv: Saturated volume (cm³)

CO₂ sequestration

After collecting the samples, the following procedures were performed by tree and species,

according to Bucci et al. (2010): Calculation of trunk volume or bole volume as

$$Tv = \frac{\pi}{4 \times DBH^2 \times H \times 0.5} \quad \text{Eq. 2}$$

where *Tv* = trunk volume (in m³), DBH = diameter at breast height, and H = tree height saturated volume.

Calculation of branch and root volume depends on such factors as species, age, and location. In this case, we estimated 25% (1.25) over the trunk volume and calculated the total volume (Eq. 3), and calculated weight (*W*, in kg) (Eq. 4).

$$1.25 \times Tv \text{ (m}^3\text{)} \quad \text{Eq. 3}$$

$$W = \rho_{bas} \times Tv \times 1000 \quad \text{Eq. 4}$$

Basic density is the relationship between absolutely dry mass and saturated volume of wood, as described in the previous item. Then, to calculate fixed carbon, we applied a factor of 0.5 to tree weight, considering that 50% of the wood consists of carbon with the remainder constituted mainly by water and nutrients. We calculated absorbed CO₂ by multiplying the fixed carbon content by 3.67, as obtained from CO₂ / C, or a ratio of 44/12.



Figure 1. Overview of the three fragments that comprise the São Paulo-Tottori Friendship Forest.

Data analyses

Cluster analyses were performed with means of clones and their variables. Later, data were standardized so that they all had a common scale, but without distorting their difference, where the mean was equal to zero, and standard deviation was equal to 1. For this standardization, the Standardize tool in the software was used. The Euclidean distance was used as a measure of

similarity, and the unweighted pair group method with arithmetic mean (UPGMA) was used to determine the groups. Through the cophenetic correlation coefficient, the dendrogram generated was evaluated. Through the generation of clusters, clone averages in their given groups were used. The analyses were performed based on the correlation between data. For the number of principal components, it was determined that the sum of two

components presented more than half of the data representation (i.e., estimated variation in the ordinate of the auto values). All analyses were performed in the R statistical software environment (R Development core team, 2021).

Results and discussion

According to table 1, we observe descriptive statistics of the variables evaluated. The maximum of 232.37 kg of fixed carbon, 852.82 kg.ha⁻¹ of sequestered carbon and considering that species in the study were 8 years old, when this information was collected, the total carbon sequestered per year (CSY) was 106.60 kg.ha⁻¹ and carbon fixed per year (CFY) was 29.04 kg. The study by Sousa et al. (2021), evaluating seven species at 10 years of age in the PEAL, which is close to the present study, found carbon sequestration values of 850.83 kg.ha⁻¹ and 231.83 kg of fixed carbon, values close to those of the present study, despite the difference in age between the two studies.

Correlation between evaluated variables

Figure 2 shows the matrix of linear correlation coefficients between dendrometric characteristics and wood density for all species evaluated. It was possible to observe strong

correlations between dendrometric characteristics and fixed and sequestered carbon. However, wood density, the only wood property studied, was negatively correlated with all other analyzed variables. The same was observed by Freitas et al. (2015), as density is a complex property to be evaluated and present interference of genetic and environmental sampling, and additionally varies longitudinally and radially within the same tree and between species. Another factor that limits the discussion about basic density is that many species in the study do not have a clear technological characterization in literature, which restricts the possible effects of basic density on dendrometric characteristics and its effect on carbon fixation and sequestration. For dendrometric variables, strong correlations were observed. For DBH, an easy variable to be measured and very important to increment is the average growth of a forest for industrial or commercial purposes. We observed a strong positive correlation ($R^2 = 0.96$) between DBH and fixed or sequestered carbon, and consequently influenced other variables such as stem volume (SV), total volume (TV), tree height (H), and weight (g or kg). In other words, there is a relationship between the greater the growth in height and width, the greater the capture and sequestration of carbon.

Table 1. Descriptive statistics of the variables analyzed in the study.

Statistics	H (m)	DBH (cm)	DM (kg. m ⁻³)	SV (m ³)	TV (m ³)	W (g)	W (kg)	F (kg)	S (kg. ha ⁻¹)	CSY (kg. ha ⁻¹)	CFY (kg)
Minimum	1.45	1.10	0.25	0.00	0.00	64.50	0.06	0.03	0.11	0.01	0.00
Mean	5.94	9.05	0.65	0.04	0.05	38131.30	38.13	19.06	69.96	8.74	2.38
Maximum	14.00	33.28	1.17	0.50	0.63	464757.10	464.75	232.37	852.82	106.60	29.04

H = tree height, DBH = diameter at breast height, DM = dry mass, SV = stem volume, TV = total volume, W = weight, F = fixed CO₂, S = sequestered CO₂, CSY = carbon sequestered per year, CFY = carbon fixed per year.

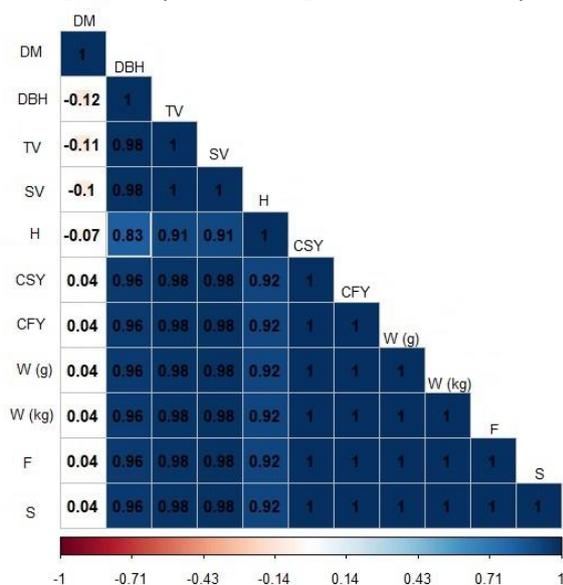


Figure 2. Correlation between all variables. H = tree height, DBH = diameter at breast height, DM = dry mass, SV = stem volume, TV = total volume, W = weight, F = fixed CO₂, S = sequestered CO₂, CSY = carbon sequestered per year, CFY = carbon fixed per year.

Fernandes et al. (2007) studied the influence of DBH on carbon fixation and sequestration in 12-year-old *Hevea* sp., and found that the greater the DBH and tree height, the greater carbon concentration in the soil, and in the tree; in this same study, these variables were the ones that most reflected in the adjustments of mathematical models to predict how much a certain tree has the capacity for carbon sequestration and fixation.

In the cluster analysis, species were grouped into four groups, with different characteristics between them. The species in cluster 1 showed similarities in relation to DBH, SV (stem volume), TV (total volume), weight, total and per year fixed and sequestered carbon. Species grouped in cluster 2, presented the lowest absolute values in relation to the other clusters, with no emphasis on any evaluated variable, i.e., from 35 species, 28 fit, as they did not present any characteristic dendrometric highlighted. Cluster 3 presents H (height), as predominant characteristic in the grouping. Density separated group 4. Table 2 shows mean values that determined the groupings. According to table 3, 12 botanical families were identified from 35 species, totaling 175 trees

analyzed in the three forest fragments of São Paulo-Tottori Friendship Forest. Regarding the frequency and quantity of species, the most representative family was Fabaceae, followed by Bignoneaceae and Malvaceae, Verbenaceae and the other families had only one species with a frequency of 2.86%. Souza (2018), evaluating carbon concentration

capacity in two distinct areas, one managed and other unexplored in the city of Manaus, between 2005-2010, reports higher stocks and increases of carbon for Fabaceae, due to rapid growth with shade tolerance, should be prioritized in afforestation to reduce environmental noise and carbon sequestration.

Table 2. Mean values of the variables of interest for each cluster (C) formed.

Cluster	H (m)	DBH (cm)	DM (kg. m ⁻³)	SV (m ³)	TV (m ³)	W (g)	W (kg)	F (kg)	S (kg. ha ⁻¹)	CSY (kg. ha ⁻¹)	CFY (kg)
1	9.05	24.30	0.81	0.23	0.29	237.04	237.04	118.52	434.97	54.37	14.81
2	5.15	6.71	0.62	0.01	0.02	12.48	12.48	6.24	22.91	2.86	0.78
3	10.61	18.44	0.59	0.15	0.19	114.92	114.93	57.46	210.89	26.36	7.18
4	6.82	12.58	0.90	0.07	0.09	83.04	83.04	41.52	152.38	19.04	5.19

H = tree height, DBH = diameter at breast height, DM = dry mass, SV = stem volume, TV = total volume, W = weight, F = fixed CO₂, S = sequestered CO₂, CSY = carbon sequestered per year, CFY = carbon fixed per year.

Table 3. Frequency and number of botanical families in São Paulo-Tottori Friendship Forest.

Family	Number	Frequency (%)
Fabaceae	18	51.42
Bignoneaceae	5	14.28
Malvaceae	2	5.71
Verbenaceae	2	5.71
Solanaceae	1	2.86
Apocynaceae	1	2.86
Calophyllaceae	1	2.86
Lecithydaceae	1	2.86
Salicaceae	1	2.86
Lythraceae	1	2.86
Myrtaceae	1	2.86
Polygonaceae	1	2.86
Total	35	100

Dendrogram of formed clusters

According to table 3, the formation of dendrograms with respective clusters of similarity and cophonetic correlation (0.9) can be observed. Multivariate analysis of variance revealed that clusters formed differ significantly from each other ($p < 0.0001$). The significant number of species in Fabaceae family (Table 3) led to grouping (Figure 3). As tree species in the family are taller, present higher values of carbon sequestration and fixation, weight in grams and in kilo and wood density. The species grouped in cluster 3 present average heights of 11.06m, with emphasis on *Solanum mauritianum* with an average height of 12.9m, followed by *Senegalia polyphylla* (10.3m), and *Piptadenia gonoacantha* (9.9m). The species from other groups have an average of 5.5m. Expressing the rapid growth potential of these native species to be used in reforestation in the urban environment. However, it was observed that species with taller trees were not those that indicate the greatest potential for concentrations of fixed and sequestered carbon and DBH. The species in group 1, composed of *Clitoria fairchildiana* and *Samanea tubulosa*,

present 92.30 and 126.65 kg of fixed carbon, respectively, and 338.75 to 464.81 kg. ha⁻¹ of sequestered carbon.

The other 33 species together present 13.03 kg of fixed carbon and 47.84 kg. ha⁻¹ of sequestered carbon. These two species (group 1) are adopted for planting when high carbon sequestration and fixation at earlier ages is desired. We verified in literature that explain the high capacity of a certain species in carbon sequestration due to its density, e.g., Sousa et al. (2021).

We did not observe this pattern in our study, since species in group 4, comprising Angico-branco (*Anadenanthera colubrina*) and Angico-do-cerrado (*Anadenanthera peregrina* var. *falcata*) had higher densities ranging from 0.838 to 0.970 g. cm⁻³, and have lower carbon sequestration and fixation capacity than other species in the study. The characteristics that most explain carbon sequestration and fixation in our study were crown volume, total volume and DBH.

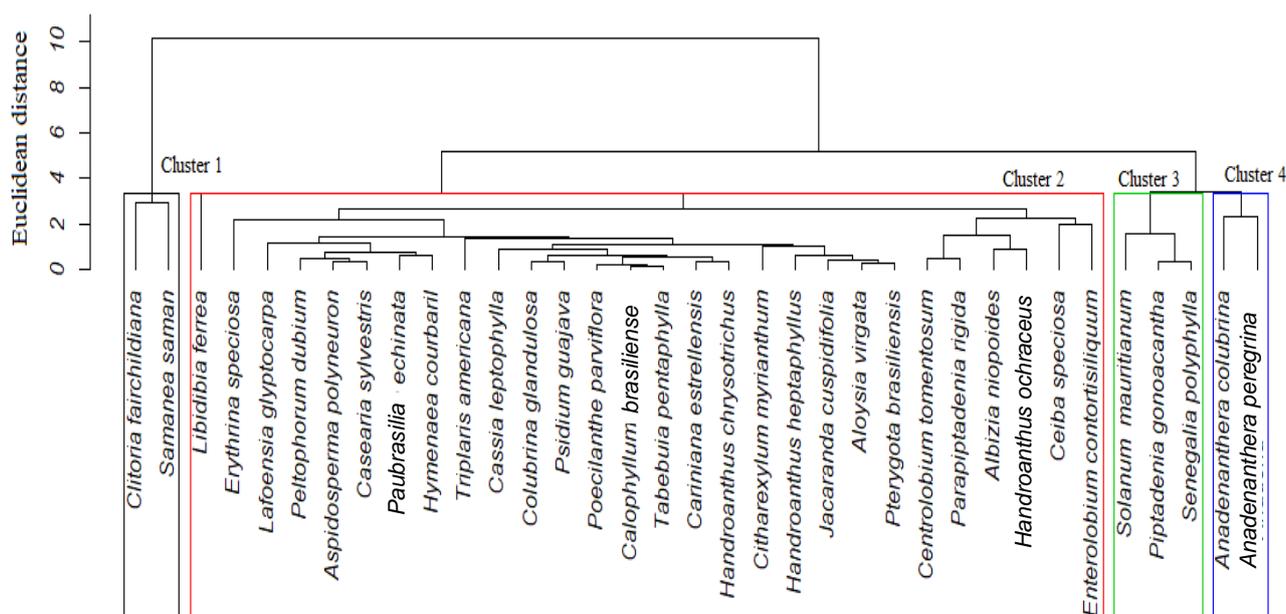


Figure 3. Dendrogram obtained from the cluster analysis.

Conclusion

We observed differences in values between the average carbon contents of species and their compartments, demonstrating that use of specific carbon contents is essential for an accurate carbon stock survey. There was also a high incidence of significant differences between carbon content values from other studies for the same species, suggesting the need to use a satisfactory amount of repetitions to estimate them, reducing the error probability and increasing the accuracy of the averages for estimates at older ages.

The species with highest potential for carbon sequestration and fixation at eight years of age in the three fragments were *Clitoria fairchildiana* and *Samanea tubulosa* 92.30 and 126.65 kg of fixed carbon, respectively, and 338.75 to 464.81 kg.ha⁻¹ of sequestered carbon, being superior and statistically different from species formed from other groups.

Among 28 species of group 2, from 35 species that we studied, there was no outstanding characteristic related to carbon sequestration and fixation, a result that may be associated with the age of the plants at the time of evaluation. The numerical difference, as well as the botanical classification or the physiological process of carbon fixation, were not the main requirements for separation of group 2. We suggest here, the need for more studies in clusters focusing on other variables that influence the sequestration process and carbon fixation of group 2 species for better understanding.

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